# Climate, development, and malaria: an application of FUND

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# CLIMATE, DEVELOPMENT AND MALARIA: AN APPLICATION OF *FUND*

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**Abstract**

Climate change may well increase malaria morbidity and mortality. This would slow economic growth through increased spending on health care, reduced production, and less effective education. Slower economic growth would increase the incidence of malaria morbidity and mortality. The integrated assessment model *FUND* is used to estimate the strength of this negative feedback. Although climate-change-induced health problems may well substantially affect the projected growth path of developing regions, it is unlikely that climate change would reverse economic growth.

**Keywords**

climate change, malaria, integrated assessment, economic growth, poverty traps

## 1. Introduction

Casual observation shows that hotter countries are generally poorer, despite some notable exceptions like Kuwait and Singapore. The renewed attention of economics to growth, income distribution and geography has led to the conclusion that hot implies poor, even when controlling for all other known or suspected determinants of economic growth (e.g., Gallup *et al*., 1999; Masters and McMillan, 2001). This finding has implications for climate change, but one cannot simply transpose a spatial effect (hotter means poorer) to a temporal effect (warming means slower growth), not without knowing the mechanisms behind the observed phenomenon (e.g., Schneider, 1997). Unfortunately, the empirical literature on climate and economic development is still inconclusive as to the mechanisms that relate climate to economic growth. The possible exception to this is health.

Health risks are greater in hotter places, particularly if these places are wet as well (e.g., McMichael *et al.*, 1996). Ill-health is an impediment to economic development, as labour productivity and education efficacy are down. At the same time, poverty – and the malnutrition, bad sanitation and deficient health care that come with it – implies ill-health (e.g., Sachs and Maleney, 2002). On the one hand, this explains the difficulty in interpretation data and the problems with equating time and space. On the other hand, it opens the possibility of a poverty trap (Azariadis, 1996): one is ill because one is poor, and one is poor because one is ill. Since global warming may well imply greater health risks, global warming may deepen or widen poverty traps – keeping people in deeper poverty, or keeping more people in poverty, or even reversing economic growth.

The prospect of climate-change-induced poverty is troubling in its own right. It increases the negative impacts of climate change and its inequity at that (Fankhauser *et al.*, 1997, 1998). It also violates some of the assumptions underlying climate change research, particularly the separation between emission scenarios and climate change impacts (Nakicenovic and Swart, 2001; see also Fankhauser and Tol, 2002). Furthermore, it complicates the trade-off for many developing countries, as well as for donors of development aid, between economic development and emission reduction (Schelling, 1995).

For these reasons, the current paper investigates the possibility and the plausibility of climate-change-induced poverty traps, using ill-health as the mechanism. Ill-health is here restricted to malaria. Malaria is a major disease, taking half a million lives each year. Malaria is a disease that has clear and well-documented links with development as well as with climate. This makes malaria an obvious starting point for an investigation like this; the conclusions suggest that it should not be the end point.

Section 2 reviews the literature on the relationships between health, wealth and climate. Section 3 present the basic model, *FUND*. Section 4 extends *FUND* to include the three-way relationship between health, wealth and climate. The extended model expands on current integrated assessments of health and climate (Chan *et al.*, 1999; Martens, 1996; McMichael, 1997). Section 5 presents results. Section 6 concludes the paper.

## 2. Previous Studies

Figure 1 shows the relationship between per capita income (PPP$, CIA, 2002) and the average annual temperature (according to the data of the Climate Research Unit; see New *et al.*, 1999). Although there are exceptions, hotter countries are generally poorer. Interestingly, if one looks separately at the "rich" countries (income above $1000) and the "poor" countries, the effect almost disappears. This suggests that there is some income threshold above which climate does not matter much, and some temperature threshold above which it is simply too hot. A climate-induced poverty trap may explain this observation. At high temperatures, all surpluses are devoted to defending against and repairing the damages done by a tropical climate; no surplus is left for investing in growth. At lower temperatures, surpluses exist and growth rapidly reduces vulnerabilities to climate and weather. Bloom *et al.* (2001b) look deeper into this issue. They find that a model with two equilibria explains the variations in income levels of countries; in the low (high) equilibrium, a country is more (less) sensitive to climate; latitude (a proxy to climate) also determines the probability of being in the high or low equilibrium. Unfortunately, Bloom *et al.* (2001b) did not test this hypothesis directly against other explanations of income distribution across the world.

Gallup *et al*. (1999) estimate the effect of climate on the level of GDP per capita as well as its growth, controlling for standard explanations of development (e.g., economic capital, human capital) but also geographic factors, mostly related to trade and transport costs. Climate indicators include average temperature, fraction of land area in the tropics, and malaria potential (in fact, a composite index of temperature and precipitation). They find that hotter countries are poorer and grow slower, and speculate that health may be the mechanism.

Masters and McMillan (2001) also find a significant influence of climate on economic development, again controlling for other explanations for growth. However, they use the number of frost days as climate indicator, arguing that frost kills pathogens for both humans and crops.

In sum, there are clear indications that climate affects the wealth of nations. Unfortunately, there is no consensus on the mechanism or strength of this relationship.

The effect of health on wealth is well-established (e.g., Blackburn and Cipriani, 2002). Bloom *et al.* (2001a) survey 14 studies on the relationship between health and growth; 13 of these 14 report a significant relationship. An increase in life expectancy stimulates growth. The estimates range from .13 to .75 additional annual economic growth for 5 additional years of expected life-time. The model of Bhargava *et al.* (2000) is the only non-linear one among the 14; they find that the effect of an increase in life expectancy is stronger for poorer countries; in fact, the effect becomes insignificant for countries with an average income above $7000/year.

The effect of climate on health is also well-established (Dowlatabadi, 1997; Haines and Fuchs, 1991; Haines and Parry, 1993; McMichael *et al.*, 1996; Patz and Martens, 1997). Martens *et al.* (1995, 1997), Martin and Lefebvre (1995), Matsuoko and Kai (1995) and Morita *et al.* (1994) estimate the effects of climate change on the potential of malaria, concluding that global warming would extend malaria risks in altitude and latitude. Tol (2002a,b) combines the estimated changes in malaria potential of these studies with current mortality and morbidity (according to Murray and Lopez, 1996a,b), assuming that changes in malaria incidence are proportional to changes in malaria potential.

The effect of wealth on health is undisputed, but not often quantified at the macro-scale. Tol and Dowlatabadi (2001) extend Tol (2002a,b) to include per capita income to explain the difference between malaria potential and incidence. Tol and Dowlatabadi (2001) estimate a linear relationship between per capita income and malaria incidence, and a threshold income of $3100/person/year above which malaria is absent.

In this paper, we further extend the malaria model to include the effect of malaria on economic growth. In the model developed below, we include the effect of health on wealth as well as the effect of wealth on health. This creates a negative feedback loop, which under certain combinations of parameters and circumstances may lead to a poverty trap. Furthermore, we introduce the effect of climate on health, so that we can study a potential climate-change-induced poverty trap.

## 3. The Model

The model used is version 2.6 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). Version 2.6 of *FUND* is the same as version 1.6, described and applied by Tol (1999a-e, 2001, 2002c), except for the impact module, which is described by Tol (2002a,b) and updated by Tol (2002d).[1] A further difference is that the current version of the model has 16 instead of 9 regions. The current version also has feedbacks from vector-borne diseases on economic development, a feature that was omitted in previous versions of the model.

Essentially, *FUND* consists of a set of exogenous scenarios and endogenous perturbations. The model is specified for 16 major world-regions: USA, Canada, Western Europe, Japan and

[1] More information and the source code of the model can be found at http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/fund.html.

South Korea, Australia and New Zealand, Central and Eastern Europe, former Soviet Union, Middle East, Central America, South America. South Asia, Southeast Asia, China, North Africa, Subsaharan Africa, and Small Island States; see Table A1 in the Appendix. The model runs from 1950 to 2200, in time steps of a year. The prime reason for starting in 1950 is to initialise the climate change impact module. In *FUND*, climate impacts are assumed to depend on the impact of the year before, to reflect the process of adjustment to climate change. Because the starting values in 1950 cannot be approximated very well, climate impacts (both physical and monetised) are misrepresented in the first few decades. This would bias optimal control if the first decades of the simulation coincided with the first decades of emission abatement. Similarly, the 22nd century is included to provide the forward-looking agents in the 21st century with a long time horizon. The calculated optimal emission reductions in 2100-2200 have little meaning (or policy relevance) in and of themselves.

The *IMAGE* database (Batjes and Goldewijk, 1994) is the basis for the calibration of the model to the period 1950-1990. Scenarios for the period 2010-2100 are based on the EMF14 Standardised Scenario, which lies between IS92a and IS92f (cf. Leggett *et al.*, 1992). Note that the original EMF14 Standardised Scenario had to be adjusted to fit *FUND*'s nine regions and yearly time-step. The period 1990-2010 is a linear interpolation between observations and the EMF14 Standardised Scenario. The period 2100-2200 is an extrapolation of the EMF14 Standardised Scenario.

The scenarios concern the rate of population growth, economic growth, autonomous energy efficiency improvements, the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide.

The scenarios of economic and population growth are perturbed by the impact of climate change. Population falls with climate change deaths, resulting from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to affect only the elderly, non-reproductive population. The other sources of mortality do affect the number of births. Heat stress only affects urban population. The share of urban in total population is based on the World Resources Databases (WRI, 2000); if is extrapolated with a simple statistical relationship between urbanisation and per capita income, estimated from a cross-section of countries in 1995. Population also changes with climate-induced migration between the regions. Immigrants are assumed to assimilate immediately and completely with the host population.

The tangible impacts of climate change are dead-weight losses to the economy. Consumption and investment are reduced, without changing the saving's rate. Climate change thus reduces long-term economic growth, although at the short term consumption takes a deeper cut. Economic growth is also reduced by carbon dioxide emission abatement.

The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be sped up by abatement policies.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of carbon dioxide emission reductions on economy and emissions, and the impact of the damages of climate change on the economy and the population.

Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted:

$$(1) \qquad C_t = C_{t-1} + \alpha E_t - \beta\left(C_{t-1} - C_{pre}\right)$$

where $C$ denotes concentration, $E$ emissions, $t$ year, and *pre* pre-industrial. Table 1 displays the parameters for both gases.

The atmospheric concentration of carbon dioxide follows from a five-box model:

$$\text{(2a)} \qquad Box_{i,t} = r_i Box_{i,t} + 0.000471 a_i E_t$$

with

$$\text{(2b)} \qquad C_t = \sum_{i=1}^{5} a_i Box_{i,t}$$

where $\alpha_i$ denotes the fraction of emissions $E$ (in million metric tonnes of carbon) that is allocated to box $i$ (0.13, 0.20, 0.32, 0.25 and 0.10, respectively) and $r$ the decay-rate of the boxes ($r$ = exp(-1/lifetime), with life-times infinity, 363, 74, 17 and 2 years, respectively). The model is due to Maier-Reimer and Hasselmann (1987), its parameters are due to Hammitt *et al.* (1992). Thus, 13% of total emissions remains forever in the atmosphere, while 10% is—on average—removed in two years. Carbon dioxide concentrations are measured in parts per million by volume.

Radiative forcing for carbon dioxide, methane and nitrous oxide are based on Shine *et al.* (1990). The global mean temperature $T$ is governed by a geometric build-up to its equilibrium (determined by radiative forcing $RF$), with a half-time of 50 years. In the base case, global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents, so:

$$\text{(3)} \qquad T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50} \frac{2.5}{6.3 \ln(2)} RF_t$$

Global mean sea level is also geometric, with its equilibrium level determined by the temperature and a life-time of 50 years. Temperature and sea level are calibrated to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

The climate impact module is based on Tol (2002a,b). A limited number of categories of the impact of climate change are considered: agriculture, forestry sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, energy consumption, water resources, and unmanaged ecosystems.

People can prematurely die (because of temperature stress or vector-borne diseases) or migrate (because of sea level rise). These effects, like all impacts, are monetized. The value of a statistical life is set at 200 times the per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set at 3 times the per capita income (Tol, 1995, 1996), the value of immigration at 40% of the per capita income in the host region (Cline, 1992). Dryland and wetland loss due to sea level rise are explicitly modelled. Dryland loss is valued at \$4 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). Dryland value is assumed proportional to GDP per square kilometre. Wetland loss is valued at \$2 million per square kilometre on average in the OECD in 1990 (cf. Fankhauser, 1994). Wetland value is assumed to be logistic in per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to dike building and consequent coastal squeeze.

Other impact categories (agriculture, forestry, energy, water, ecosystems) are directly expressed in money, without an intermediate layer of impacts measured in their ‘natural’ units (cf. Tol, 2002a).

Damage can be due to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damage in the rate of temperature change slowly fades, reflecting adaptation (cf. Tol, 2002b).

Impacts of climate change on energy consumption, agriculture and cardiovascular and respiratory diseases explicitly recognise that there is a climate optimum. A mix of factors, including plant physiology and farmer behaviour, determines the climate optimum. Impacts are positive or negative depending on whether climate is moving to or away from that optimum climate. Impacts are larger if the initial climate is further away from the optimum climate. The optimum climate concerns the potential impacts. Actual impacts lag behind potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to the new climate are always negative (cf. Tol, 2002b).

Other impacts of climate change, on coastal zones, forestry, unmanaged ecosystems, water resources, malaria, dengue fever and schistosomiasis, are modelled as simple power functions. Impacts are either negative or positive, but do not change sign (cf. Tol, 2002b).

Vulnerability changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanisation) and ecosystems and health (with higher values from higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector-borne diseases (with improved health care) (cf. Tol, 2002b).

Carbon dioxide emissions are calculated on the basis of the Kaya identity. Emission can be modified by policy, e.g., through a carbon tax. The costs of emission reduction are subject to learning by doing, so that emission abatement now reduces emission abatement costs later. The exact specification is given by Tol (2002e). This paper is not considering greenhouse gas emission reduction.

## 4. Modelling Malaria

A vector-borne disease like malaria may intensify and spread with warmer and more humid conditions. Currently disease-free areas, such as the highlands of Ethiopia, Kenya and Indonesia (WHO, 1990) as well as Australia, Southern Europe and the south of the USA (Haines and Fuchs, 1991), may be invaded. Although many studies refer to this effect in a qualitative sense, only a few attempts to quantification have been reported.

Three model studies support the analysis here. Martin and Lefebvre (1995) indicate under $2xCO_2$ an increase of 7-28%, depending on the GCM used, in the land areas where malaria can be potentially transmitted. Martens *et al.* (1995, 1997; cf. Martens, 1997) expect several millions of additional malaria cases by the year 2100. Morita *et al.* (1995) indicate a 10-30% increase in the number of people at risk from malaria under $2xCO_2$. Martens *et al.* (1995, 1997) standardize their results to an increase in the global mean temperature of 1.16°C. Martin and Lefebvre (1995), and Morita *et al.* (1994), however, present their results (for malaria only) for various increases in the global mean temperature (2.8°C to 5.2°C). Both studies suggest that the relationship between global warming and malaria is linear. For these three studies, the GCM-specific estimates of the increase in global malaria death toll have been scaled by the corresponding increase in the global mean temperature and then averaged. Next, the averages of the three studies have been averaged. The yearly, regional death toll due to malaria was taken from Murray and Lopez (1996a,b), expressed as fraction of total population. Relative mortality is assumed to increase uniformly over the world. Table 2 summarizes the findings.

Vulnerability to vector-borne diseases strongly depends on basic health care and the ability to purchase medicine. These factors are assumed to be linearly related to per capita income. The data of the WHO (Murray and Lopez, 1996a,b) suggest a linear relationship between per capita income and mortality due to malaria, schistosomiasis, and dengue fever for the Middle

East, Latin America, and South and Southeast Asia. Centrally Planned Asia (too low mortality) and Africa (too high) mortality are outliers. A regression of vector-borne mortality and per capita income suggests that populations with an income above \$3100 per head, with a standard deviation of \$260/head, are not vulnerable to vector-borne diseases. Because of the outliers, the standard deviation is increased to \$1000/head.

The model for malaria is thus:

$$(13)\, m_{r,t} = a_r T_t^{b} \left( \frac{y_c - y_{t,r}}{y_c - y_{1990,r}} \right)^{g} \; if \quad y_{t,r} \le y_c$$

while $m_{t,r}$=0 if $y_{t,r}$>$y_C$; $m$ denotes mortality; $t$ denotes time; $r$ denotes region; $\alpha$ is parameter, the benchmark impact of climate change on malaria; cf. Table 2; $y$ denotes per capita income; $T$ denotes the change in the global mean temperature relative to 1990; $y_C$ is a parameter, denoting the per capita income at which vector-borne mortality becomes zero; $y_C$=\$3100 (2100-4100); $\beta$ and $\gamma$ are parameters, denoting the non-linearity of mortality in temperature and income, respectively; $\alpha$=1 (0.5-1.5); $\gamma$=1 (0.5-1.5).

The effect of malaria on economic growth is modelled as follows. As above, we only consider the effect of a *deviation* of malaria from its (no-climate-change) baseline. Gallup *et al.* (1999) estimate that malaria reduces economic growth in Africa, where most malaria occurs, by up to 1% per annum. Murray and Lopez estimate that the maximum incidence of malaria is 1.66 deaths per thousand per year. As Gallup *et al.* use a linear model, we thus have that an additional malaria death per thousand reduces growth by 1/1.66=0.6%. This is my best guess. Below, the results of a wide-ranging sensitivity analysis are reported.

The model now has a three-way interaction. Climate change increases malaria. Economic growth reduces malaria, and malaria reduces economic growth. If the climate change effect is strong enough, malaria will increase enough to reverse economic growth, which in turn would lead to more malaria and less growth.

## 5. Results

Figure 2 presents per capita incomes in Sub-Saharan Africa for various strengths of the effect of malaria on economic growth. Climate-change-induced malaria slows growth perceptibly, but does not reverse growth, not even when the parameter is five times as large as its best guess value (perhaps the maximum credible parameter value). Indeed, an analytically tractable approximation of the model suggests that the effect of malaria on economic growth has to be at least 30 times as large as the best guess in order to reverse growth.

Figure 3 displays a sensitivity analysis around Figure 2. Without the malaria effect, Sub-Saharan incomes are projected to grow to some \$17,000 per person per year. With the malaria effect, and all parameters set at their best guesses, this value falls by about \$700. If malaria is more than linear in temperature (â=1.5 in Equation 13), income falls by some \$800. If malaria is less than linear in per capita income (ã=0.5 in Equation 13), income falls by about \$900. If the malaria feedback parameter is doubled, income falls by some \$1500. A higher sensitivity of malaria to climate change (cf. Table 2) cuts income by about \$1600. The largest effect, however, is due to the climate sensitivity; increasing this to 4.5°C for 2x$CO_2$ leads to an income loss of about \$3800.

Figure 4 repeats Figure 2, but now with the climate sensitivity set to its high value. Figure 3 indicates that the climate sensitivity is the parameter with the greatest effect. Without an impact of malaria on economic growth, per capita income reaches some \$14,000 per person per year in 2200. With the malaria effect of growth, per capita income falls, but growth is not reversed. The maximum malaria effect reduces per capita income by some \$7,000 – in Figure 2, this is only \$3,000.

Figure 5 repeats Figures 2 and 4, but now baseline economic growth is much lower (and, in fact, more consistent with the last 50 years of African development). In this case, climate-change-induced malaria does reverse economic growth, but only if the parameter is set four times as large as its best guess value.

In sum, climate change may reverse economic growth through an increase in malaria. However, this is only observed if climate change is rapid, economic growth is slow, and the effect of ill-health on growth is large. Although this possibility cannot be excluded, one would have to push parameters outside of their typical range to observe this effect.

## 6. Discussion and conclusion

The key question of this paper is whether climate change may reverse economic growth by increasing the incidence of vector-borne diseases, particularly malaria. The preliminary conclusion is that this is unlikely. Although the mechanism is in place in a qualitative sense, quantitatively it is fairly weak. Only if parameters and scenarios deviate strongly from what is commonly assumed can climate change induce a health-related poverty trap.

That said, the numerical results do indicate that the separation of greenhouse gas emission scenarios from climate change impacts is misleading. Climate change may noticeably slow economic growth, particularly in poorer regions.

Unlikely as a climate-change-induced health-poverty trap may seem at the spatial resolution of the *FUND* model, the fact that there is small chance of something to happen for the whole of Subsaharan Africa implies that there is a much larger probability of this happening for a country or region. Particularly the sensitivity to baseline economic growth – unlikely to be uniform over Africa – suggests that parts of Subsaharan Africa may face a reversal of economic growth because of climate change.

The above findings are preliminary because the data are weak and our understanding is incomplete. Furthermore, the model used misses several processes and details that may crucially change the results. Public health in poor countries is an area of active intervention by rich-world donors. A deterioration of the health situation, whether climate change induced or not, may trigger an intensification of foreign aid, mitigating or even reversing the decline. However, history shows that this is not automatic and that help is not always successful.

Malaria disproportionally affects the young. The effect of malaria on economic growth is therefore primarily through education. The model includes neither age structure nor education, implicitly keeping these the same as in the mid 1990s, the period for which the model's parameters were estimated and calibrated. However, one can imagine that a reduction in economic growth would increase fertility rates. This would spread educational resources more thinly, while the increased malaria risks would reduce the incentives to invest in educating vulnerable children. This would strengthen the negative feedback loop found above.

The analysis above ignores progress in medical technology. A cheap and reliable malaria vaccin would remove all issues. However, it may also be that a gradual disappearance of malaria would cut the market for malaria medicine and hence R&D, rendering the remaining pockets of malaria more vulnerable.

Finally, there is more to health than malaria. Other diseases may increase as well with climate change. A reduction in local food supply and a slowdown of economic growth and hence the ability to import food would increase a population's vulnerability to health effects. The same holds true for water resources, where import substitution is more limited.

In sum, climate change may well, via deleterious health effects, slow economic growth. The preliminary analysis in this paper suggests that climate change is unlikely to reverse growth, but there are good reasons to believe that the results here are biased. Future research should establish the strength of the biases, and the sign of the overall bias.


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Table 1 Parameters of equation (1).

| Gas | $\alpha$[a] | $\beta$[b] | pre-industrial concentration |
|---|---|---|---|
| Methane ($CH_4$) | 0.3597 | 1/8.6 | 790 ppb |
| Nitrous oxide ($N_2O$) | 0.2079 | 1/120 | 285 ppb |

[a] The parameter $\alpha$ translates emissions (in million metric tonnes of $CH_4$ or $N_2O$) into concentrations (in parts per billion by volume).

[b] The parameter $\beta$ determines how fast concentrations return to their pre-industrial (and assumedly equilibrium) concentrations; $1/\beta$ is the atmospheric life-time (in years) of the gases.

Source: After Schimel *et al*. (1996).

Table 2. Malaria mortality and morbidity and their sensitivity to global warming.

| Region | Mortality | | | Morbidity | | |
|---|---|---|---|---|---|---|
| | Current[a] | Change[b] | | Current[c] | Change[d] | |
| USA | 0 | 0.0 | (0.0) | 0 | 0.0 | (0.0) |
| CAN | 0 | 0.0 | (0.0) | 0 | 0.0 | (0.0) |
| WEU | 0 | 0.0 | (0.0) | 0 | 0.0 | (0.0) |
| JPK | 0 | 0.0 | (0.0) | 0 | 0.0 | (0.0) |
| ANZ | 0 | 0.0 | (0.0) | 0 | 0.0 | (0.0) |
| EEU | 0 | 0.0 | (0.0) | 0 | 0.0 | (0.0) |
| FSU | 0 | 0.0 | (0.0) | 0 | 0.0 | (0.0) |
| MDE | 14 | 2.1 | (1.5) | 350 | 5.2 | (3.8) |
| CAM | 32 | 2.8 | (2.1) | 140 | 1.3 | (0.9) |
| SAM | 32 | 7.4 | (5.3) | 140 | 3.4 | (2.4) |
| SAS | 31 | 27.5 | (19.9) | 500 | 45.0 | (32.5) |
| SEA | 113 | 40.0 | (29.0) | 370 | 13.1 | (9.5) |
| CHI | 0 | 0.0 | (0.0) | 40 | 4.1 | (3.0) |
| NAF | 14 | 1.3 | (0.9) | 350 | 3.2 | (2.3) |
| SSA | 1435 | 591.4 | (428.1) | 5300 | 218.5 | (158.1) |
| SIS | 32 | 1.1 | (0.8) | 140 | 0.5 | (0.4) |

[a] Deaths per million.

[b] Thousand deaths per degree centigrade.

[c] Years of life diseased per million people.

[d] Thousand years of life diseased per degree centigrade.

Table A1. The regions in *FUND*.

| Acronym | Name | Countries |
|---|---|---|
| USA | USA | USA |
| CAN | Canada | Canada |
| WEU | Western Europe | Andorra, Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Sweden, Switzerland, United Kingdom |
| JPK | Japan and North Korea | Japan, North Korea |
| ANZ | Australia and New Zealand | Australia, New Zealand |
| CEE | Central and Eastern Europe | Albania, Bosnia and Hercegovina, Bulgaria, Croatia, Czech Republic, Hungary, FYR Macedonia, Poland, Romania, Slovakia, Slovenia, Yugoslavia |
| FSU | Former Soviet Union | Armenia, Azarbaijan, Belarus, Estonia, Georgia, Kazakhstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan |
| MDE | Middle East | Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Turkey, Unit Arab Emirates, West Bank and Gaza, Yemen |
| CAM | Central America | Belize, Costa Rica, El Salvador, Guatamala, Honduras, Mexico, Nicaragua, Panama |
| SAM | South America | Argentina, Bolivia, Brazil, Chile, French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuala |
| SAS | South Asia | Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka |
| SEA | Southeast Asia | Brunei, Cambodia, East Timor, Indonesia, Laos, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Taiwan, Thailand, Vietnam |
| CHI | China plus | China, Hong Kong, North Korea, Macau, Mongolia |
| NAF | North Africa | Algeria, Egypt, Libya, Morroco, Tunisia, Western Sahara |
| SSA | Subsaharan Africa | Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Congo-Brazzaville, Congo-Kinshasa, Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe |
| SIS | Small island states | Antigua and Barbuda, Aruba, Bahamas, Barbados, Bermuda, Comoros, Cuba, Domenica, Domenican Republic, Fiji, French Polynesia, Grenada, Guadeloupe, Haiti, Jamaica, Kiribati, Maldives, Marshall Islands, Martinique, Mauritius, |

| | |
|---|---|
| | Micronesia, Nauru, Netherlands Antilles, New Caledonia, Palau, Puerto Rico, Reunion, Samoa, Sao Tome and Principe, Seychelles, Solomon Islands, St Kitts and Nevis, St Lucia, St Vincent and Grenadines, Tonga, Trinidad and Tobago, Tuvalu, Vanuatu, Virgin Islands |

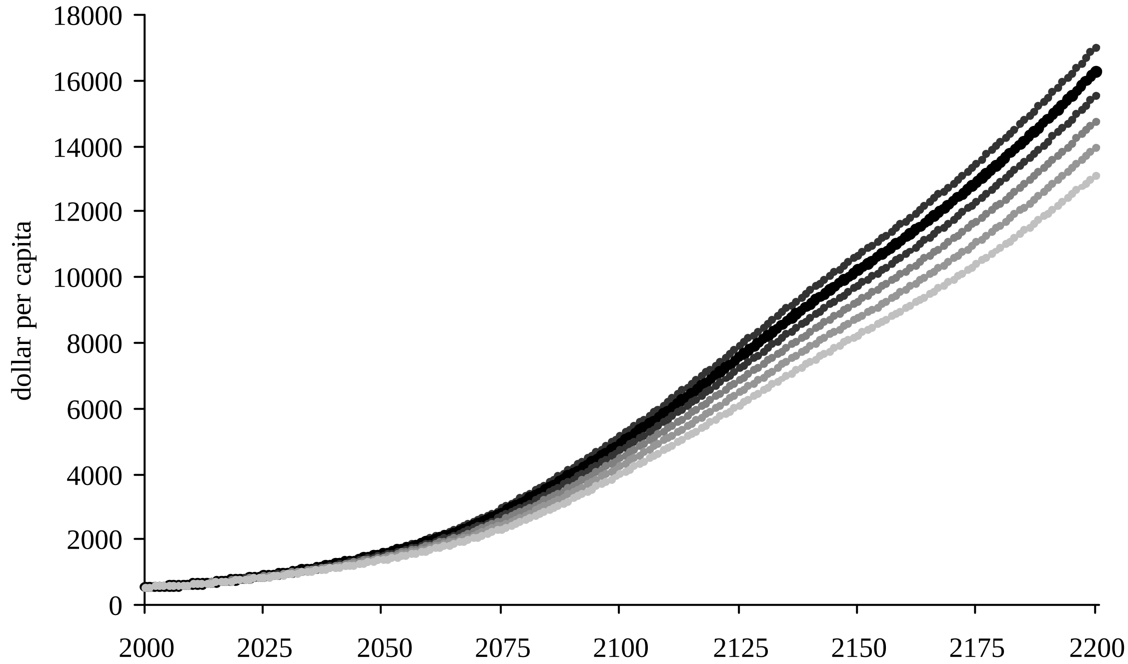


Figure 2. Per capita income in Subsaharan Africa for various strengths of the effect of malaria on economic growth. The parameter assumes values of, from top to bottom, 0.0 (no feedback), 0.6 (best guess), 1.2, 1.8, 2.4 and 3.0.

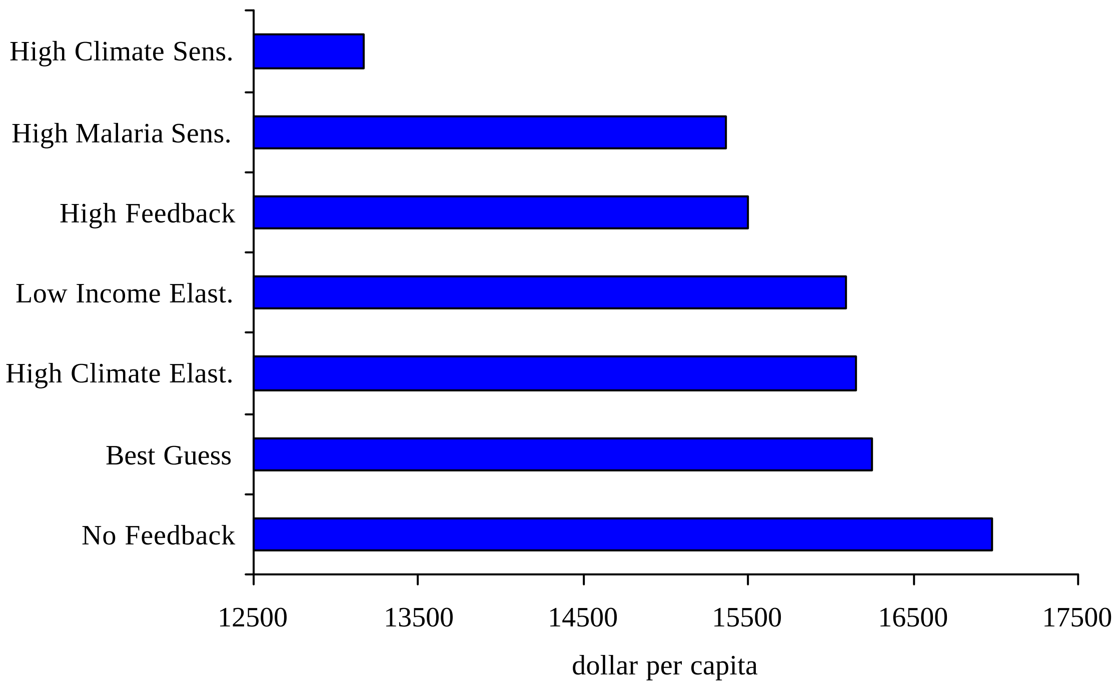


Figure 3. Per capita income in Sub-Saharan Africa in 2200 under various parameter settings that govern the effect of malaria on economic growth.

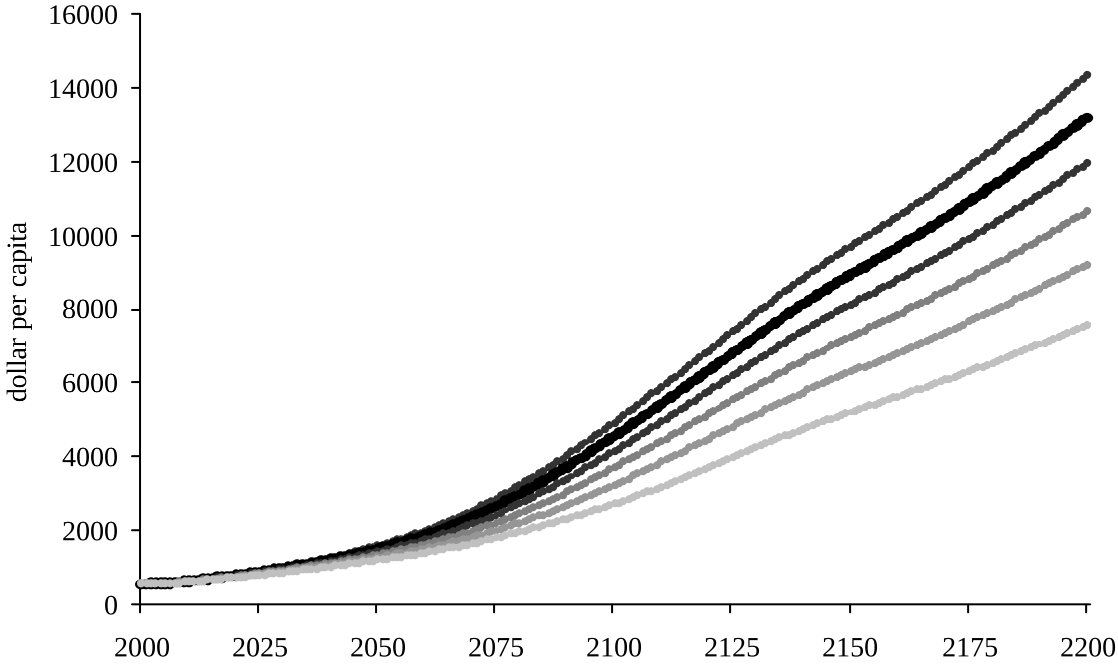


Figure 4. Per capita income in Subsaharan Africa for various strengths of the effect of malaria on economic growth. The parameter assumes values of, from top to bottom, 0.0 (no feedback), 0.6 (best guess), 1.2, 1.8, 2.4 and 3.0. The climate sensitivity is an equilibrium warming of 4.5°C for a doubling of the atmospheric concentration of carbon dioxide; in Figure 1, the climate sensitivity is 2.5°C.

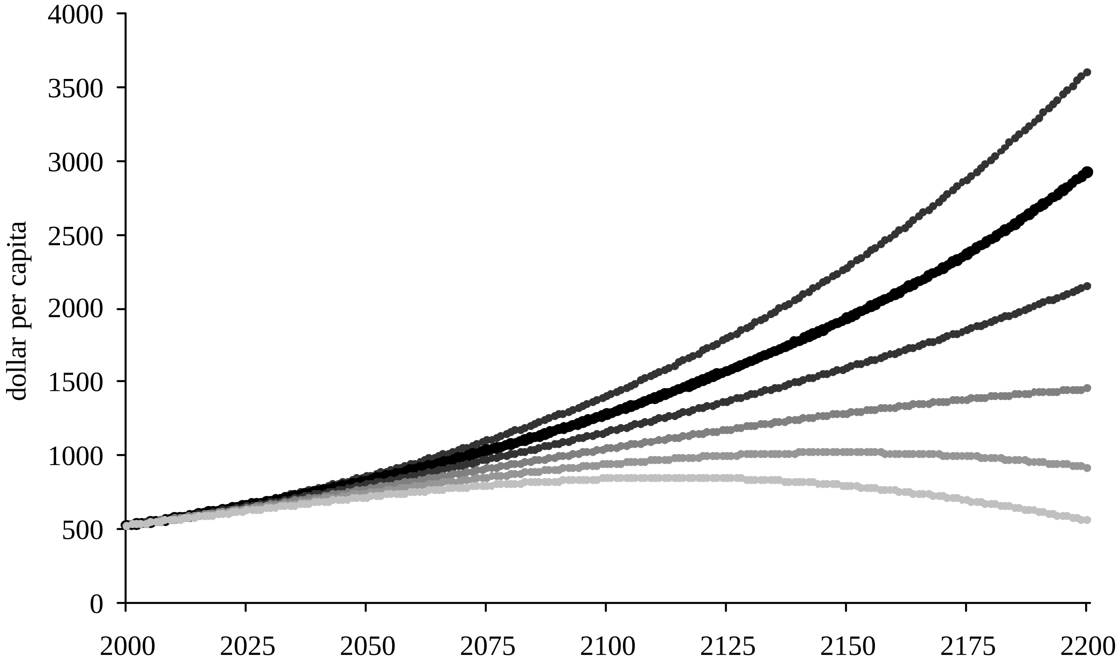


Figure 5. Per capita income in Subsaharan Africa for various strengths of the effect of malaria on economic growth. The parameter assumes values of, from top to bottom, 0.0 (no feedback), 0.6 (best guess), 1.2, 1.8, 2.4 and 3.0. The baseline economic growth is 1% per capita throughout the entire century; in Figure 1, economic growth is assumed to be 2.5% between 2010 and 2030, falling steadily to 1% in 2100.

## Working Papers

## Research Unit Sustainability and Global Change

## Centre for Marine and Climate Research, Hamburg University, Hamburg

Tol, R.S.J. (2002), *Climate, Development, and Malaria: An Application of* FUND, **FNU-16** (submitted).

Hamilton, J.M. (2002), *Climate and the Destination Choice of German Tourists*, **FNU-15** (submitted).

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